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May 31, 2004

Dr. Arje Nachmann
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4015 Wilson Blvd, Mail Room 713
Arlington, VA 22203

Subject: Final Report for AFOSR Grant F49620-01-1-0057
Covering period: 01/10/00-28/02/04

Dear Dr. Nachman,

Below is our final report on the aforementioned grant sponsored by your office.

a. Summary of the Research Effort

(1) *Laser transmission model development.* We developed a number of 2D radiative transfer models based on the successive-order-of-scattering approach for the computation of airborne high-energy laser transmission and backscattering through homogeneous and inhomogeneous thin cirrus clouds in both plane-parallel and spherical geometries. These models took into account the relative positions of aircraft, target, and cirrus clouds in the atmospheres.

We investigated the sensitivity of laser transmission and backscattering on variation of the cloud optical depth, particle size, and cloud-base height, as well as the positions of aircraft and target. We also evaluated the effects of the earth's sphericity on laser transmission and backscattering. A paper describing our detailed research findings has been published in Applied Optics (Ou, et al. 2002).

Our present research involves the theoretical formulation of a three-dimensional direct and first-order transmission-backscattering model for thin cirrus.

(2) *Laboratory experiment and instrument development.* The experimental program has been designed to measure the single-scattering property of highly anisotropic ice crystals with a polar nephelometer and the extinction of a laser beam through cirrus using a transmissometer, both in the laboratory and in situ. The nephelometer measurements can be directly compared to the theoretically computed phase functions, which are the fundamental building blocks of the radiative transfer program. Moreover, with the concurrently measured ice crystal size and shape distributions, we can cross check the laser transmission computed from the model with the transmission measured by the transmissometer. We conducted a number of laboratory experiments and tests using the polar nephelometer and transmissometer in the cloud chamber at the Desert Research Institute (DRI). This unit consists of a 3 m tall and 0.5 m in diameter growth column positioned above a larger cold chamber and has the capability of generating uniform ice crystal size and shape.

Further laboratory experiments will be carried out in collaboration with the DRI scientists to enhance our fundamental understanding of the optical properties of ice crystals generated in the DRI cloud chamber, particularly associated with the ice-crystal orientation.

(3) *Participation in the balloon experiment planning.* The purpose of the balloon experiment is to measure directly with the transmissometer the extinction of a laser beam that traverses cirrus clouds for comparison to the extinction determined indirectly from the laser transmission model using the simultaneously measured ice crystal size distribution and their single-scattering properties from the cloud scope, a video microscope that images ice particles, and two polar nephelometers. In collaboration with the ABL System Program Office, a balloon of about 141,000 ft^3 capacity will be used to carry four instruments: two nephelometers, one transmissometer, and one cloud scope (DRI). A lidar (PEELS) to be furnished by the scientist at the Hanscom AFB will also be deployed at the experimental site to measure the cloud height and other cloud parameters with a vertical and horizontal resolution of about 30 meters. The balloon experiment will be conducted under the MODIS (Terra/Aqua satellites) passes so that coincident and collocated satellite data can be collected for the retrieval of cirrus optical depth and ice crystal size, input parameters that are required for the laser transmission model. The outputs of all of these instruments in the balloon will be sent directly to the ground control for storage and real time analysis by the participating scientists. The first such experiment will be carried out in late October 2003 in the vicinity of southern New Mexico.

In the experiment, one polar nephelometer measures the light scattered into a two-dimensional plane by particles that intercept a 780 nm 100 milliwatt laser beam using fiber optic light guides and photodiode detectors. The other nephelometer is similar, but uses a visible (670 nm) laser and has 44 channels of detection. The ice particles are isolated to a 14 mm^3 volume and are pulled continuously through the instrument using vacuum pumps at a constant rate of 7 cm^3 / second. Each instrument has an onboard CPU and data acquisition card and has been reprogrammed to operate autonomously when used on the balloon. A complete description of the nephelometer has been provided in Barkey et al. (2002) and Barkey and Liou (2000). The transmissometer, designed specifically for this program, uses a folded optical path to measures the extinction of a visible laser beam over a very long (80 m) path length. A scientific paper on the design of the instrument and pertinent results is under preparation.

In addition to supporting the laser transmission model development, a successful balloon experiment will provide for the first time the scattering phase functions for ice particles in the atmosphere. It will also provide in situ data for validation of the satellite remote sensing of cirrus clouds.

(4) *Satellite remote sensing of thin cirrus.* Thin cirrus clouds, sometimes being subvisual as observed from the ground, interact significantly with laser energy by means of long-path transmission, and can pose a critical risk to the ABL operation. Thus, it is

vitally important to accurately detect the presence of these clouds. We have developed a thin cirrus detection scheme using a combination of the 1.38 μm reflectance, the 8.6-11 μm brightness temperature difference, and the 0.65 μm reflectance. Large 1.38 μm reflectance results only from high clouds due to strong low-level water vapor absorption, while large brightness temperature difference is produced because the difference in the imaginary indices of refraction of ice between 8.6 and 11 μm is larger than that of liquid water. This scheme has been applied to two distinct cloud scenes over the Southern Great Plains site established by the DOE Atmospheric Radiation Measurement (ARM) program on March 22 and April 16, 2001 during the Terra/MODIS overpasses. We used the collocated cloud radar backscattering results to validate the satellite detection scheme with significant success (Roskovensky and Liou 2003a, b).

b. Publications Acknowledging the AFOSR Grant Support

(1) S. C. Ou, Y. Takano, K. N. Liou, R. J. Lefevre, and M. W. Johnson, 2002: Laser transmission-backscattering through inhomogeneous cirrus clouds. *Appl. Opt.*, 41, 5744-5754.

(2) Barkey, B., M. Bailey, K. N. Liou, and J. Hallett, 2002: Light scattering properties of plate and column ice crystals generated in a laboratory cold chamber. *Appl. Opt.*, 41, 5792-5796.

(3) J. K. Roskovensky, and K. N. Liou, 2003a: Detection of thin cirrus using a combination of 1.38-μm reflectance and window brightness temperature difference. *J. Geophys. Res,* (September, in press).

(4) J. K. Roskovensky, and K. N. Liou, 2003b: Detection of thin cirrus from 1.38 μm/0.65 μm reflectance ratio combined with 8.6-11 μm brightness temperature difference. *Geophys. Res. Lett.,* (October, in press)

c. Academic and Industrial Activities

(1) A copy of the 2D laser transmission/backscattering program for both plane-parallel and spherical geometries has been delivered to Jim Bunting of AFRL and Ron Furnier and Haig Iskendarian of Northrop-Grumman-TASC. This program was used to determine the attenuation of high-energy laser beam through cirrus clouds. During the reporting period, it was integrated into a decision aid package to estimate the effectiveness of a laser-based system. Within this system, the cirrus optical depth and ice crystal size inferred from satellites can be incorporated in the laser transmission model.

(2) On February 10, 2003, B. Barkey traveled to DRI to test the new 44-channel nephelometer along with the existing 33-channel unit.

(3) On May 26, 2003, B. Barkey traveled to DRI to conduct tests on the nephelometers in preparation for the balloon experiment.

(4) On June 10, 2003, B. Barkey and S. C. Ou traveled to the Kirtland Air Force Base to participate in a technical interchange meeting concerning the balloon experiment.

(5) On September 23-26, 2003. K. N. Liou, S. C. Ou, and B. Barkey will be attending the transmission conference and the ABL workshop to be held in the Boston area.

d. Current Support

The current AFOSR grant supports (1) K. N. Liou, Professor and Director/IRRS; (2) Y. Takano, Associate Research Scientist; (3) S. C. Ou, Senior Research Scientist, and (4) B. Barkey, Research Associate.

Respectfully submitted,

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Professor and Director
UCLA Department of Atmospheric Sciences

Cc: Lt Col Randy Lefevre
Nancy Hom/Jeanne Ladner, Grant Manager, Atmospheric Sciences